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FINITE ELEMENT ANALYSIS OF RESIDUAL STRESSES IN 2CR-MO REPAIR WELDS INCLUDING TRANSFORMATION PLASTICITY

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FINITE ELEMENT ANALYSIS OF RESIDUAL STRESSES IN 2Cr-Mo REPAIR WELDS INCLUDING TRANSFORMATION PLASTICITY

by

A. S. ODDY

ABSTRACT

Welding is frequently used in the repair of pressure vessels. Accurate prediction of the residual stresses caused by welding is important to the safe operation of a pressure vessel especially when post-weld stress relief is not feasible. This report outlines some of the experience generated in the three-dimensional (3D) finite element analysis of welds. In particular, the importance of transformation plasticity to the prediction of residual stresses is examined. Transformation plasticity occurs when the stresses generated by the transformation of individual grains, interact with the macroscopic stress state to produce plastic strains. Although the laws governing plastic deformation still apply, the stress state changes over distances of the order of the grain size. It is impractical to perform finite element analyses with grain-sized elements. Heuristic methods requiring empirical constants have been used in the past. A method based on the fundamental laws of plasticity and basic material properties is proposed to incorporate transformation plasticity in a finite element program. The transformation plasticity which occurs, depends on the stress state present in the material. During any time step the stress state can change substantially. If the step size is too large the analysis may become unstable. A method which allows larger steps while eliminating the instability and improving the convergence is presented. Repair welds are usually shorter than the length required to create the quasi-stationary steady state, necessitating a three-dimensional (3D) analysis. A (3D) analysis of a short longitudinal pipe weld in a typical pressure vessel steel is given. For the conditions analysed, the inclusion of transformation plasticity lowered the predicted maximum longitudinal residual tensile stress by 137 MPa. Residual stresses predictions must include transformation plasticity.

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ANALYSE PAR ÉLÉMENTS FINIS DES CONTRAINTES RÉSIDUELLES DANS LES SOUDURES DE RÉPARATION 2Cr-Mo, EN TENANT COMPTE DE LA PLASTICITÉ DE TRANSFORMATION

par

A.S. ODDY

RÉSUMÉ

On recourt souvent au soudage pour réparer les récipients sous pression. La prévision exacte des contraintes résiduelles causées par le soudage est importante pour le fonctionnements sûr d'un récipient sous pression, particulièrement lorsqu'il est impossible de libérer les contraintes après soudage. Ce rapport décrit des expériences réalisées en analyse tridimensionnelle (3D) de soudures par éléments finis. En particulier, il traite de l'importance de la plasticité de transformation dans la prévision des contraintes résiduelles. La plasticité de transformation intervient lorsque les contraintes causées par la transformation de grains individuels interagit avec l'état macroscopique des contraintes pour produire des déformations plastiques. Même si les lois régissant la déformation plastique s'appliquent toujours, l'état des contraintes varie sur des distances de l'ordre de la taille des grains. Il n'est pas pratique de procéder à une analyse par éléments finis sur des éléments de la taille des grains. Des méthodes heuristiques comportant des constantes empiriques ont été utilisées dans le passé. Une méthode s'appuyant sur les lois fondamentales de la plasticité et les propriétés de base des matériaux est proposée pour tenir compte de la plasticité de transformation dans un programme aux éléments finis. La plasticité de transformation en jeu dépend de l'état des contraintes dans le matériau. Pendant un intervalle de temps donné, l'état des contraintes peut varier considérablement. Si l'intervalle est trop grand, l'analyse peut devenir instable. Une méthode permettant des intervalles plus grands tout en éliminant l'instabilité et en améliorant la convergence est présentée. La longueur des soudures de réparation est en général plus courte que la longueur requise pour établir le régime quasi permanent, nécessitant une analyse tridimentionnelle (3D). Une analyse 3D d'une soudure droite courte dans un tuyau en acier de qualité récipient sous pression est décrite. Dans les conditions d'analyse, la prise en compte de la plasticité de transformation a abaissé de 137 MPa la valeur maximale prévue de la contrainte de traction résiduelle longitudinale. Les prévisions des contraintes résiduelles doivent tenir compte de la plasticité de transformation.

INTRODUCTION

The thermal cycle imposed on any welded object causes a cycle of thermal expansion and contraction. The expansion and contraction varies with time and location. Because this expansion/contraction is not uniform, stresses appear as regions near the weld are restrained by regions further away. Plastic deformation, occurring as a result of these stresses leads to residual stresses in the object after the temperatures have returned to ambient levels. Thus the use of welding in the repair of pressure vessels introduces residual stresses in the weld itself and in the base metal. In the fusion zone (FZ) itself, and extending out some distance into the base material is a region of tensile residual stresses. These residual stresses are usually of yield point magnitude. Post-weld stress relief is often done to reduce these stresses but may not be feasible in many instances. An accurate knowledge of the magnitude and distribution of the residual stresses is useful when assessing the fitness of the repaired vessel. The objectives of this study are two. First, it is intended to show the importance of transformation plasticity in predicting residual stresses. The second objective is to summarize some of the general guidelines uncovered in the finite element analysis of welds.

Prediction of the residual stresses is difficult because temperatures and thus thermal expansion vary with time and location. The residual stresses are the result of the elasto-plastic response, of the object, to the transient thermal stresses generated by the thermal cycle. In addition, both thermal and mechanical properties are temperature dependent. Numerical models are required because of the complexity of the phenomena involved. Finite element analysis (FEA) has been used by many authors[1][2][3][4] to predict residual stresses in welding. Accurate calculation of the residual stresses requires that all important contributory processes be modelled. This report outlines some of the progress that has been made towards the rigorous prediction of residual stresses in welds. One phenomenon which has received attention in recent years is the effect of phase transformations. Two processes occur during transformations which can influence the residual stresses present. The first is the reversible volume change associated with the change in crystal structure. The second is an irreversible plastic deformation[5] known as transformation plasticity. Dubois[3], using a relation based on empirical constants, has shown that neglecting transformation plasticity can seriously alter the residual stresses predicted in an overlay weld. In this report, the effect of neglecting transformation plasticity will be demonstrated by doing a

three-dimensional (3D), finite deformation, finite element analysis of a short repair weld. A recently developed relation[6] for transformation plasticity, which does not rely on empirical constants, will be used.

Accurate prediction of the thermal cycle in the weld is the first requirement when predicting residual stresses. Prediction of the temperature field requires a nonlinear, transient, 3D analysis with temperature dependent material properties. The heat generated by the plastic deformation is much less than that introduced by the weld itself. Thus the thermal analysis may be performed separately from the mechanical analysis. It will be assumed here that the complete thermal history is already known. An extensive body of knowledge exists in the literature for those interested in the prediction of the thermal history of welds by the finite element method. A partial list is included here[1][2][7][8][9].

Once the thermal history is known it is necessary to calculate the thermal strains and plastic deformation which occur. Finite element analysis of thermal-elasto-plasticity in welds has been treated extensively in the literature[1][4]. Several questions of practical interest to the analyst have not been adequately dealt with. The decay in elastic properties which occurs as the material approaches its melting temperature means that elasto-plastic constitutive models will fail at high temperatures. It has been traditional to ignore the softening above some cutoff temperature. Guidelines for the magnitude of this cutoff have been generally lacking. The choice of thermal strain field is another important question which has not been examined.

THEORY

Thermal-elasto-plastic constitutive models[2][10] decompose the total strain rate $\dot{\epsilon}_{ij}^{Tot}$ into the elastic $\dot{\epsilon}_{ij}^{E}$, plastic $\dot{\epsilon}_{ij}^{P}$, and thermal $\dot{\epsilon}_{ij}^{Th}$ strain rates. A creep strain rate is sometimes included. Creep strains are usually not significant in the analysis of welds. During phase transformations additional terms, $\dot{\epsilon}_{ij}^{TrV}$; i.e., the volume change associated with the transformation and $\dot{\epsilon}_{ij}^{TrP}$; i.e., the transformation plasticity are included[11][12][13]. Leblond et al.[14]have shown that the plastic strain rate can be decomposed into terms representing classical plasticity and transformation plasticity. Thus the total strain rate becomes,

$$\dot{\epsilon}_{ij}^{Tot} = \dot{\epsilon}_{ij}^{E} + \dot{\epsilon}_{ij}^{P} + \dot{\epsilon}_{ij}^{Th} + \dot{\epsilon}_{ij}^{TrV} + \dot{\epsilon}_{ij}^{TrP} \tag{1}$$

The volume change associated with the transformation is often included as part of the

thermal expansion by modifying the coefficient of thermal expansion[1][2][15]. Separation of the volume change from the thermal expansion allows more flexibility in the description of the material.

An important consideration in the thermal stress analysis of welds is the order of the temperature field used to calculate the thermal strains. It might seem reasonable, when calculating thermal strains, to use the same interpolation functions for the temperature field as are used for the displacement field in each element. This however, leads to an incompatibility between the total and thermal strain fields. The total strains ϵ_{ij}^{Tot} are formed from the derivatives of the displacements. Thus, the polynomial describing the total strain field in the element will be one order lower than that describing the displacements. If the same interpolation functions are used for the displacements and temperatures, the total strains will, therefore, be one order lower than the thermal strains. Thus, temperature fields for which an unrestrained element ought to be able to deform stress free may, in fact, create spurious stresses. Of course, if the mesh is fine enough, the temperature field becomes uniform over each element and the strain fields become compatible regardless of the choice of interpolation functions. It will, therefore, only be in areas where the temperature field changes rapidly that these incompatible fields will appear. In the thermal-stress analysis of welds this condition exists near the weld itself.

In the course of this investigation it was found that the use of compatible strain fields is imperative. Although predicted and measured residual stresses were in agreement at a distance from the weld the use of incompatible thermal and total strain fields has been found to lead to significant inaccuracies in the residual stresses predicted near the weld[16]. In that region the predicted residual longitudinal stress was compressive whereas the measured value was tensile. This failure to make accurate predictions near the weld has also been observed by Lindgren et al.[4]. In that paper, the longitudinal residual stresses in a single pass weld were in good agreement everywhere except near the fusion zone. There, the predicted longitudinal stresses were compressive whereas the experimentally measured stresses were tensile. The use of a thermal strain field which is compatible with the total strain field is necessary, especially in regions near the weld itself. This implies that an important condition for thermal stress analysis is that the thermal strain and total strain fields be compatible. This requirement appears most strongly in areas where the temperature field changes rapidly. Since elements with linear displacement fields were used in the

work reported here, the stress analysis calculated thermal strains that were constant within each element.

It is the plastic deformation occurring during the thermal cycle that results in the residual stresses. A rough rule of thumb states that plastic deformation will occur in any part of the weldment whose peak temperature is more than 100°C greater than the initial temperature. The region of plastically deformed material is, therefore, much greater than the fusion zone (FZ) and heat-affected zone (HAZ). An important part of a material's response is the reduction in elastic properties at high temperatures. As the material approaches its melting temperature, the elastic modulus and yield strength decline to zero. At some point the use of an elasto-plastic constitutive model becomes inappropriate. The analysis may also become unstable if the properties are permitted to decrease to zero. It has been traditional to select some cutoff temperature, above which further decay in the elastic properties is not acknowledged. In the past[17], the cutoff had been selected as that temperature at which the yield stress was 1% of its room temperature value. In attempting the analysis of 2Cr-Mo repair welds it became apparent that this was not good enough. Severe convergence problems were encountered until the cutoff temperature was reduced to ensure that the yield strength was never less than 10% of the room temperature value. The cutoff temperature became 900°C for the 2Cr-Mo steel used in this investigation.

Temperature dependent material properties were used in both the thermal and stress analyses. For the 2Cr-Mo steel used in this investigation the transformation to austenite was assumed to occur linearly between 723°C and 900°C with an accompanying 1.1% decrease in the volume. Two of the most important characteristics which distinguish one steel from another is the magnitude of the yield stress and its variation with temperature. Values of the yield stress for normalized and simulated heat-affected zone (HAZ) material at various temperatures have been obtained from Alberry et al.[18]. The yield stress of the normalized material was much lower than that of the simulated HAZ. At room temperature, the yield stress of normalized 2Cr-Mo was 560 MPa. In this analysis, the body started out with normalized properties. Any point which transformed to austenite was changed to receive the simulated HAZ value for yield stress listed by Alberry[18]. This alloy exhibits an austenite to bainite transformation between 600°C and 400°C with an associated 2.0% increase in volume[18][19]. This transformation was assumed to be linear with temperature. The other thermal and mechanical properties were assumed to be similar to that of the

structural steel used by Andersson[1].

In displacement-based nonlinear finite element analysis, it is customary, in the first iteration, to predict the driving forces using the conditions at the beginning of the increment. Thermal strains, volume changes and transformation plasticity are manipulated to contribute to the forces. Displacements and deformations are then predicted. Integration over the increment produces a final state which is checked to ensure that equilibrium is satisfied. If it is not, residuals are computed, and a new iteration begun.

TRANSFORMATION PLASTICITY

The presence of phase transformations can play a significant role in the stresses present in a weld. There are two ways in which a phase transformation can affect the stress history of a weld. During a phase transformation there is a reversible volume change. In steels the austenite decomposition is accompanied by an expansion of between 1% and 4% depending on the composition and transformation temperature. In addition to the reversible volume change there is often an irreversible but finite plastic deformation[5]. This deformation is irreversible in the sense that transformation back to the original phase does not undo the deformation. In fact, it may enhance the deformation. This deformation depends on the stresses present in the material. This phenomenon does not depend on the transformation time and ceases when the transformation is complete. It is therefore not creep related. This irreversible plastic deformation, occurring during a phase transformation has been called transformation plasticity.

Two mechanisms are responsible for transformation plasticity. The first mechanism is driven by the volume change which occurs during the transformation. When a small volume of material transforms and changes volume, it generates stresses in itself and in the surrounding untransformed material. At the interface between transformed and untransformed material the stresses are large enough to cause plastic deformation in the weaker phase. These stresses have been called microscopic stresses[14][20] because the stress field changes over distances smaller than the grain size. In the absence of a macroscopic stress the plastic strains are randomly oriented and no macroscopic deformation is observed. Transformation plasticity occurs when the interaction of the microscopic and the macroscopic stresses orients the plastic strains resulting in observable deformation. This has been called

the Greenwood-Johnson mechanism[5]. The second mechanism, attributed to Magee[21] occurs in martensitic transformations. The formation of martensite plates occurs in specific crystallographic orientations. The presence of a macroscopic stress favours some directions over others in order to minimize the internal energy. Recent theoretical examinations[14][20] show that the plastic strain rate during a transformation must include terms proportional to the transformation rate. These terms correspond to the Greenwood-Johnson and Magee mechanisms. Thus new metallurgical processes are not required to describe the phenomena observed.

Transformation plasticity can be important[3][11][12] in determining the nature and magnitude of residual stresses. This is especially true of materials exhibiting low temperature phase changes. Finite element analysis (FEA) including transformation plasticity requires the ability to handle 3D stress fields, as well as time or temperature dependent stresses, phase fractions, and material properties. Many transformation plasticity models rely on empirical constants[3][11][12]. This is inconvenient because these empirical constants are not known for most materials and must be altered when the material properties or transformation products change.

The original, uniaxial relation of Greenwood[5] has been generalized for triaxial stress states, partial transformations and incremental analyses[6]. The resulting relation for the incremental transformation plasticity $\Delta\epsilon_{ij}^{TrP}$ is,

$$\Delta\epsilon_{ij}^{TrP} = \frac{5}{4}\frac{\Delta V}{V}\frac{1}{Y}S_{ij}(2 - 2z_{(n)} - \Delta z)\Delta z \tag{2}$$

where Y is the the flow stress in the weaker phase, $\Delta V/V$ is the specific volume change associated with the transformation, S_{ij} is the deviatoric stress tensor, $z_{(n)}$ is the fraction already transformed at the start of the increment and Δz is the amount which transforms during the increment. The need for empirical constants has been removed. Transformation plasticity can be predicted from familiar material properties. The derivation retains the yield function and associated flow rule as originally proposed by Greenwood and Johnson. Changes in yield strength and volume change which occur at different temperatures can be included.

The transformation plasticity strains depend on the stress state. A rapid decrease in the stress is common during a transformation. Use of the initial stress for S_{ij} in equation

2 overestimates the transformation plasticity. This causes oscillations in the stresses if the increments are too large. Temperature changes of less than 20°C per step are often required to avoid this numerical instability. This is not practical in a 3D analysis.

Transformation plasticity stops if the deviatoric stresses become zero. Clearly, transformation plasticity cannot cause a stress change larger than the initial stress. A useful measure of the severity of the incremental transformation plasticity is

$$\Phi = \frac{|D_{ijmn}\Delta\epsilon_{mn}{}^{TrP}|}{|S_{kl}|} \tag{3}$$

where D_{ijmn} is the elastic material property tensor. This represents the ratio of the magnitude of the stress change, if all other strains are zero, to the magnitude of the initial stress. Values of Φ greater than 20 are common in the analysis of welds. When transformation plasticity was originally included[17] in the analysis of welds the instability caused by the overestimation of the transformation was avoided by using Φ as a scaling factor. If Φ was greater than 1 it was used to limit the magnitude of the transformation plasticity strains. Although functional, this was inadequate in several respects. Before the transformation starts a tensile deviatoric stress often exists in the material. The volume change associated with the transformation is often large enough to overcome this tensile stress and create compressive stresses. This reversal in the sign of the deviatoric stress means that the transformation plasticity strains should also reverse sign. If, on the other hand, the tensile stresses increased as a result of activity elsewhere in the body, then the predicted transformation plasticity would be much too low. Clearly a subincrementation scheme was needed during the integration over the time step.

A subincrementation scheme was implemented for the integration over each time step in the analysis. It was found that the subincrementation alone was able to remove the instability. The scaling factor Φ was retained and used in two ways. First, it was used to set the number of subincrements in the integration over the time step. A practical number of subincrements is $10 \times \Phi$ to a maximum of 50. Even though subincrementation alone is sufficient to eliminate the numerical instability it was found that overestimates of the transformation plasticity in the first iteration retard convergence. In the first iteration of any increment the transformation plasticity may be calculated using the initial stress. If Φ is greater than 1 it is used as a scaling factor to reduce the magnitude of the predicted transformation plasticity. Using Φ to limit the transformation plasticity predicted in the

first iteration improves convergence.

Subincrementation eliminates the numerical instability and limiting the initial prediction of the transformation plasticity improves convergence. These strategies do not automatically guarantee accuracy. As in all nonlinear analyses, too large an increment can still cause an inaccurate prediction.

METHOD

The effect of neglecting transformation plasticity on the residual stresses in a short repair weld was examined. A 3D, nonlinear, transient, finite deformation, FEA program[17], using the Green-Naghdi stress rate and centred strain analysed the residual stresses in a short weld. Comparisons of residual stresses predicted numerically with those measured experimentally for other welds have shown acceptable accuracy[17][22][23].

A short axial weld in a pipe was selected as a typical situation in which welded repair might be considered. The initial problem requiring repair might have been that of a partial penetration axial flaw. By imposing an axial weld, the largest residual stresses would be oriented in the most favourable direction. The pipe selected had a wall thickness of 9.5 mm (0.375 in.) and an inner diameter of 304.8 mm (12 in.). Only a portion of the pipe was analysed to reduce the expense. The section analysed was 203.2 mm (8 in) long and covered 127.0 mm (5 in.) of the circumference. This patch is shown in Fig. 1. The weld itself was 101.6 mm (4 in.) long, located on the upper boundary of the patch, running along the outer edge, as depicted in Fig. 1. This plane representing the upper boundary was treated as a plane of symmetry. The net heat input was 2464 W. This could have been an MMA weld of 22 V, 160 A and assuming a thermal efficiency of 70%. The welding speed was 2.54 mm/s (6 ipm). A spherical source of 5.0 mm radius with a Gaussian power distribution was used[24]. The source was on for a total of 43 s. In the first 2 s the source was stationary. The source then travelled 101.6 mm (4 in) at 2.54 mm/s (6 ipm). At the final end of the weld the source remained stationary for a further 1 s. The material was assumed to be initially preheated to 200°C. Heat loss through radiation and surface convection was not included. Radiation and convection near the source are usually a small portion of the total heat flow. Convection losses at low temperatures may affect the thermal history but not to the extent of making serious differences to the size of the upset zone or the extent of the

plastic deformation. Conduction was assumed to dominate since the portion being analysed was only a small part of a larger mass. To simulate this larger mass the three edges which were not planes of symmetry were assumed to be far enough away from the weld that there was no increase in temperature. The mesh-grading hexahedrons of McDill et al[25] allow a 3D analysis of a short weld to be performed.

To test the effect of transformation plasticity, two stress analyses were performed. In the first, the volume change and transformation plasticity associated with the austenite decomposition were included. In the second analysis, the volume change during the austenite decomposition was included but transformation plasticity was not permitted to occur. In both cases, the extra rigidity provided by the rest of the pipe had to be included in some way. On the plane of symmetry along which the weld ran, displacements perpendicular to this plane; i.e., circumferential displacements were not permitted. On the other three edges, the stiffness of the rest of the pipe was modelled by assuming that all displacements on the boundary were zero. This is somewhat more restrictive than would be found in reality. However, increasing the restraint leads to overestimates in the residual stresses and is therefore conservative.

RESULTS

Figure 1 shows the mesh used and the temperature field calculated for 38 s after the start of welding. For the conditions analysed, the fusion zone (FZ) penetrates slightly more than half the thickness. The HAZ fully penetrates the thickness. For temperatures below about 800°C the isotherms indicate that the heat flow is 2-dimensional (2D); i.e., in the axial and circumferential directions.

Figure 2 shows the through-thickness distribution of the longitudinal (axial) residual (i.e., after temperatures have returned to ambient) stresses on the plane of symmetry, at the midlength of the weld, with and without transformation plasticity. A significant variation in the longitudinal stress through the thickness is evident. In both cases, the highest stress exists on the inner surface. Although the curves are similar in shape, with and without transformation plasticity, the magnitudes are significantly different. The inclusion of transformation plasticity has reduced the peak tensile stress. The peak tensile stress predicted excluding transformation plasticity was 337 MPa whereas the peak tensile stress

predicted including transformation plasticity was 200 MPa. Both of these values are much lower than the yield strength for heat-treated HAZ material. A possible explanation is that the low yield strength of the surrounding normalized material limits the magnitude of the stresses that can be developed in the HAZ. The through-thickness average of the longitudinal (axial) stress is approximately equal for both cases. This is not always the case. In other conditions, the inclusion of transformation plasticity has caused a substantial change in the the through-thickness average of the stress[6].

The magnitude of residual stresses present after welding is important in the prediction of the resistance to fracture. In this case the transverse or hoop stresses are of particular interest because they will influence the growth of axial flaws. Figure 3 compares the through-thickness variation of the transverse residual stress on the plane of symmetry, at the midlength of the weld. The transverse (hoop) stress is much smaller than the longitudinal (axial) stress. In both cases the largest values are found near but not at the inner surface. The inclusion of transformation plasticity has made a substantial difference in the transverse stress predicted on the inner surface. Without transformation plasticity the transverse (hoop) stress on the inner surface is 9 MPa. With it, the predicted value is 61 MPA.

The largest stresses observed were the longitudinal (axial) stresses on the inside of the pipe. Figure 4 shows the longitudinal (axial) stresses obtained on inside of the pipe, at the midlength of the weld, versus the circumferential distance from the weld centreline. Transformation plasticity only affects the stresses in and near the HAZ. In both curves, the points with the highest longitudinal stresses experienced maximum temperatures between 500°C and 700°C. It is evident that the largest longitudinal stresses exist just outside the HAZ. In the FZ itself the longitudinal stresses are much lower than the maximum values observed. This same pattern was present on both surfaces, with and without transformation plasticity. This pattern of reduced longitudinal stresses inside the HAZ with the largest stresses outside the HAZ is an unusual one. Experimental measurements do not usually show this pattern. There are, however, some experimental residual stress measurements which do show exactly this pattern. The experimental results shown by Hibbitt and Marcal[36] for welds in HY-80 steels show exactly the same pattern. This is another material which exhibits a low temperature transformation with a large volume change. The lowered stresses in the FZ and HAZ can only be the result of the volume change during

the austenite decomposition. When the material inside the FZ and HAZ transforms, the volume change will reduce the tensile stresses present in that area. Because the material is continuous, expansion inside the HAZ will increase the tensile stress in adjacent material outside the HAZ.

CONCLUSIONS

The use of incompatible thermal and total strain fields leads to erroneous predictions in the residual stresses in the FZ and HAZ.

The most likely cause of the lower longitudinal stress in the FZ and HAZ is the volume change associated with the austenite decomposition. When this transformation occurs, the expansion relieves the tensile stresses present in the FZ and HAZ while simultaneously raising the tensile stresses in the region just outside.

The presence of transformation plasticity can have a significant effect on the residual stress state in welds. Excluding transformation plasticity leads to overestimates in the longitudinal (axial) stress. This is especially true on the inner surface. Transformation plasticity can affect the magnitude and sign of the residual stresses predicted in the fusion and heat-affected zones. Thermal-stress analysis of welds in materials exhibiting phase transformations must include the effect of transformation plasticity.

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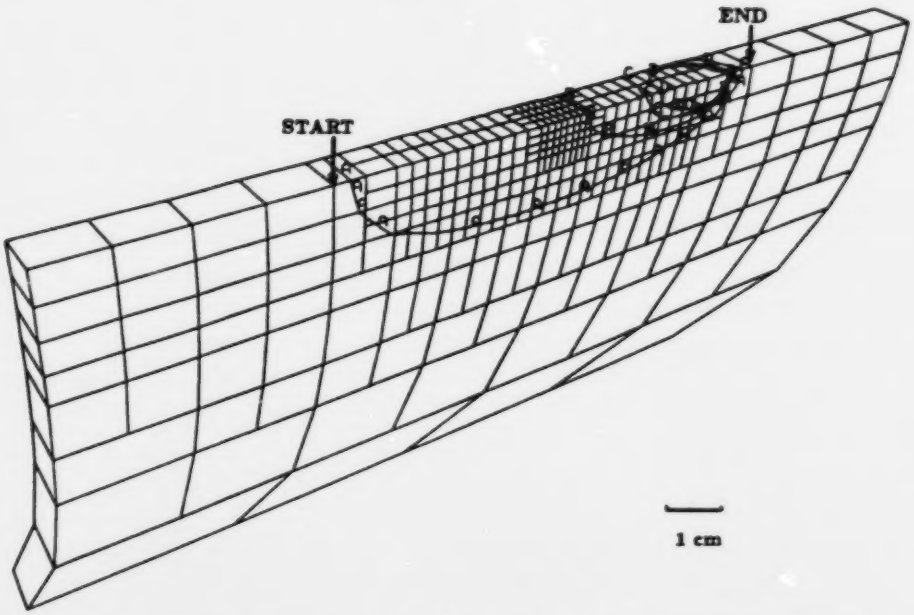

Fig. 1. Finite element mesh showing temperature distribution present at 38 sec. A 400°C; B 600°C; C 800°C; D 1000°C

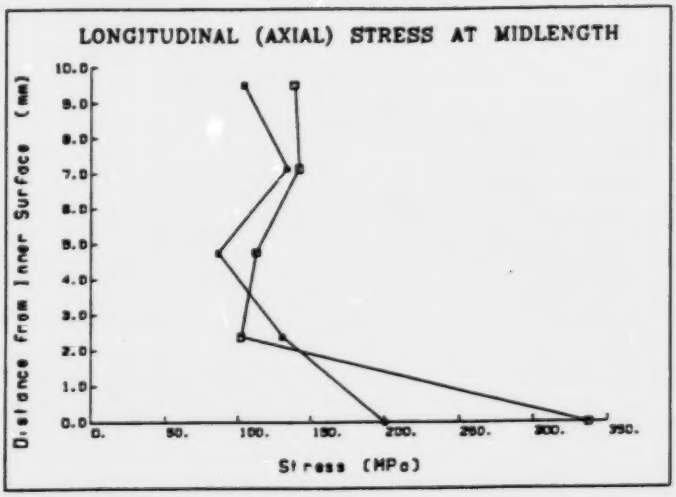

Fig. 2. Residual longitudinal (axial) stress vs distance from inner surface, at midlength.

- ■ **including transformation plasticity**
- □ **excluding transformation plasticity**

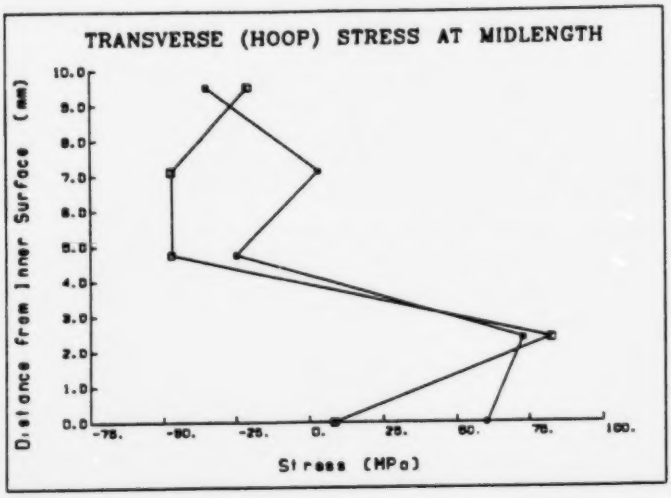

Fig. 3. Residual transverse (hoop) stress vs distance from inner surface, at midlength.

■ **including transformation plasticity**

□ **excluding transformation plasticity**

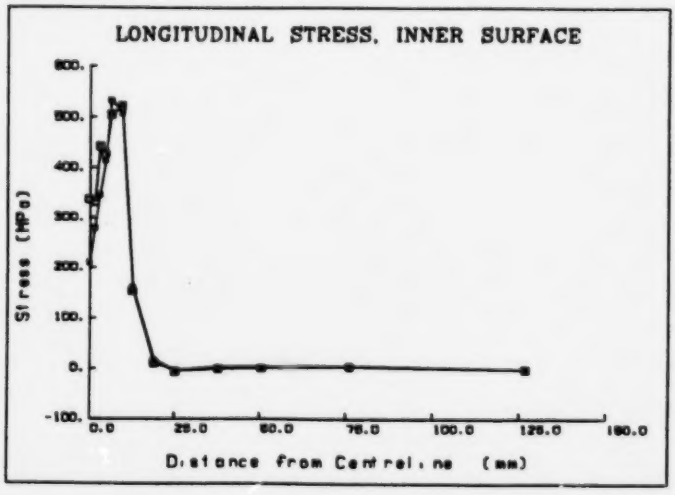

Fig. 4. Residual longitudinal (axial) stress on inner surface vs circumferential distance from weld centreline, at midlength, including transformation plasticity.

■ **including transformation plasticity**

□ **excluding transformation plasticity**